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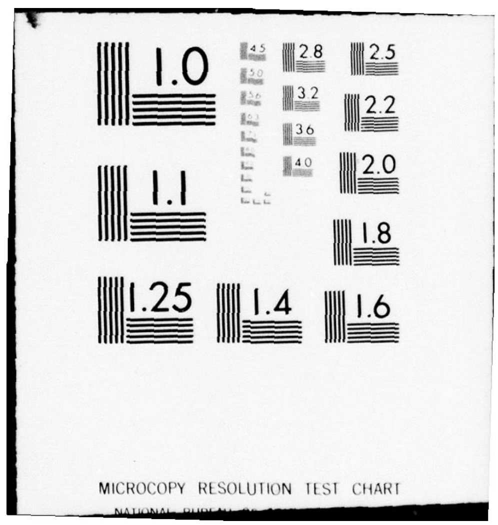
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Air Combat Accuracy Methodology Dynamic Air-to-Air Model. First Edition.

10 Harold E. /Smith

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Interactions

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This report documents the intent, structure, and treatment of accuracies in the Dynamic Air-to-Air Model, First Edition (DATAM-I). JTCG-approved, DATAM-I is available for use by all air-to-air gunnery assessment groups of the U.S. Armed Forces. The report is intended as background information for these groups and to stimulate exchange of information which may influence air-to-air gunnery/methodology.

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PREFACE

This report documents an effort to provide air-to-air gunnery assessment groups with the necessary background information to confidently exercise the Dynamic Air-to-Air Model, First Edition (DATAM-I) and to stimulate exchange of information which may influence future gunnery/methodology.

This report was drafted in May 1976, submitted to the Joint Munitions Effectiveness Manual, Anti-Air, Gunnery Effectiveness Group (JTCG/AA/GEG) for coordination in June 1976, and updated in June 1977. The effort documented in this report was conducted in support of Project 2543, Weapons Effectiveness Methodology, and by the Air Force Armament Laboratory, Armament Development and Test Center. The project engineer was Harold E. Smith (DLYD).

This report has been reviewed by the Information Officer (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

J. R. MURRAY
Chief, Analysis Division

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

A	Sight peak amplitude
AAE	Average aim error
ADC	Air data computer
AFA	Air Force Academy
ATAN	Arctangent
CADC	Central ADC
CPA	Closest point of approach
DATAM-I	Dynamic Air-to-Air Model, First Edition
E	Sight angular frequency
f	Function
g	Local acceleration in gravity units
h	Incremental change
HOT	High Order Terms
HUD	Head up display
LCOS	Lead computing optical sight
LOS	Line of sight
mil	Milliradian
MLD	Mean line of departure
MPI	Mean point of impact
PSI	Gun angle phase lead
rms	Root mean square
S	Frequency domain variable
SDF	Sight damping factor
SOA	State of the art
t, T	Time
TFW	Tactical Fighter Wing
THETAG	Gun pointing angle
THETAS	Sight pointing angle
TOF	Time of flight
TN	Sight sensitivity constant
T/W	Thrust/weight
wrt	With respect to

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SECTION I

INTRODUCTION

The objective of this report is to provide defense community standardized definitions of parameters and their known/unknown characteristics which affect air combat gunnery, and to show the methodology for their treatment in the Dynamic Air-to-Air Model, First Edition (DATAM-I). It is not intended as a treatise on the theory of fire control. That is well covered in Reference 1, which was used as the basis for formulating DATAM-I.

Any error/inaccuracy that causes a weapon to miss its target can be categorized as a fire control error. However, machine guns are not always directed to cause every projectile to hit the target. Sweeping/dispersion of the fire pattern is design-intended to cover uncertainties so that some percentage of the pattern covers the target. Thus, the definition of fire control errors can be ambiguous. One intent of this report is to provide a common basis to avoid ambiguities/misinterpretations.

The accuracy problem of any gunnery fire control effort can be readily divided into three areas; sighting accuracy, solution accuracy of the estimate/prediction, and accuracy of the estimate. During the time interval of the burst, correlations within and between the areas must also be considered. However, treating each area separately first provides a simplistic nature to a very complex overall problem. The separate treatments then form a good basis for envisioning the interactions between the areas.

A common practice in previous accuracy analyses was to assume all areas to be perfect while examining the influence of imperfections/inaccuracies of one parameter. Independent variations of individual parameters, divided by the change/interval, were modeled to determine the sensitivity of accuracy to that particular parameter. After all identified parameters were examined, it was also common practice to assign standard deviation (root mean square, rms) values for the parameters. Assignments have historically been based on very scant test data, heuristics, or educated guesswork. Similarly, the correlations of the variables as a function of time within the pass and from one pass to another have been estimated in a very cursory manner; i.e., linear or other simple regression fits have been applied to deterministic responses which are obviously several orders higher. The sensitivity and rms-value products were listed out as fire control error budgets which have one enviable quality; i.e., in the absence of substantiating data, rational arguments are difficult. Finally, error budgets have been combined in various and sundry ways. The root sum square of all, sometimes called hopper statistics, or of the correlation-coefficient modified sighting/random and solution/systematic errors has been esoterically pleasing to some who prefer the dialectical approach, while especially irritating to the plodding engineer who is diligently searching for cause and effect. Even the most

exacting can lose insight between the problem and model mechanics which sometimes determine how certain variables must be treated. Of equal importance, these analyses have invariably neglected to consider the interactions that can have significant impact on the total accuracy problem.

This report is structured to: (1) describe DATAM-I mechanics, development, and grey areas to provide the necessary insight for examining error characteristics; (2) identify parameters and their characteristics in each of the three areas; (3) examine the influence of interactions; and (4) offer conclusions and recommendations. While efforts have been made to keep heuristic offerings to a minimum, it is noted that the major purpose of the model is to forecast. Accordingly, in lieu of clairvoyance, some rules of thumb must be proffered.

SECTION II

DATAM-I MECHANICS, DEVELOPMENT AND LIMITATIONS

Originated circa 1967, DATAM-I was conceived as a parametric/sensitivity model. At that time, there were many opinions but hardly any data to substantiate the validity of specific/selected values of the parameters. As expected, its existence aided the impetus to collect data bases which have greatly narrowed the parametric uncertainties of the model. However, even though DATAM-I results show close agreement with historical data, extrapolations of the characteristics of statistical data bases to forecast the outcome of modeled events sometimes result in arguments of cause and effect. Obviously, the myriad of factors that can influence the results are uncontrollable, some undefinable. Accordingly, while complete agreement appears highly unlikely, the rewards of discovery in striving for agreement warrant the efforts of trying.

Two bases of the model which were originally considered gross simplifications have turned out to be the model's strongest attributes. One, perfect tracking of the predicted impact point is used as the basis for subsequent inclusion of sighting errors. Two, simplistic modeling of the estimated target flight path mechanics is used as the basis for defining the basic sight/estimated solution. Solution inaccuracies, estimate/target uncertainties, and interaction influences are then accounted for in a statistical manner which accommodates an efficient method for digital computer evaluations.

The obvious attribute of this type of modeling is the ability to isolate and examine individual factors, and also flexibly combine factors in any arrangement while retaining the capability to run many thousands of cases for the same time/cost of a single case using a Monte Carlo deterministic model.

Development of DATAM-I has been one of continuous evolution. The probability of hit is determined by use of a nominal diffuse target area definition in the Gun-Val equation (Reference 2). The shoe box method of determining presented areas as a function of crossing/impact angle was added to alleviate the necessity of calculating and inputting a nominal area for each geometry. Aim wander was calculated as a function of attacker load factor (Reference 3) and combined with other errors in the esoteric manner that was mentioned in Section I. Intended for Air Force Armament Laboratory evaluation of gun system design, it became obvious that the model mechanics could show improvement in effectiveness indices from overkill; i.e., excessive hits for occurrence of hitting conditions. Accordingly, detailed modeling of firelines and hit array printouts were added to ascertain that increasing firing rates did not cause excessive firing densities. Aim traces from gun camera films of Combat Hassle experiments and recent

combat documentations, and from manned simulator experiments were analyzed to determine fireline characteristics (References 4 through 8). To check the sensitivities of fireline definitions, linear, quadratic, cubic, and hyperbolic forms of differently oriented lines and variable densities along the line were modeled and compared with data-derived firelines. When this detail was found to wash out over the distribution of miss errors, linear modeling of the firelines was adopted. The linear form can be envisioned as the mean of firelines which are bent in opposite directions. Results of rate distributions along the firelines were checked and found to agree with those for the nominal rate. The nominal rate was first adopted on the heuristical bases substantiated in Reference 5 that pilots tend to normalize sighting results; i.e., efforts correlate with difficulty. Later, a heuristical g and angle-off sensitivity was adopted when it was found to match recent combat results.

Estimated target flight path mechanics, straight or turning, are modeled to show the nominal estimated or erroneously estimated path (i.e., a constant one/specified turning g path shows the error of matched-g-estimate/linear computing sights) without regard to the instantaneous orientation of the gravity vector. Note that the Lead Computing Optical Sight (LCOS) does not use verticality (gravity orientation) in its solution. With the statistical approach of DATAM-I, this serves as the basis for later addition of the inaccuracies. It is not intended to model actual target flight path mechanics.

Misinformed individuals have attempted to discredit the model as only applicable to horizontal plane engagements, stating that real world combat encompasses three dimensions. Not only have they misconstrued estimated/predicted or erroneously estimated flight mechanics to be deterministic, they would encumber the model with all known deterministic mechanics including exterior ballistics. Obviously, to deterministically model mechanics whose accuracy data bases are well known adds useless complexities to the model, wasting time/money and energy.

Data bases, used by the model, are real world. These data bases do not differentiate any of the parameters as a function of either canting of or state within the target maneuver plane. If controlled-experiment data are derived to show the sensitivity, it could easily be accounted for in the accuracy distributions, not the mechanics of the model, or variable turning g to define gravity orientation tactics can be programmed to affect the erroneous estimate. Note that the attacker g and sight limitations derived in the model are based on this estimated target flight path mechanics which is what the attacker is attempting to follow.

The simplistic mechanics of DATAM-I which provides a clear overview of what is being modeled also clearly shows its grey areas/limitations. DATAM-I data bases define its capabilities and limitations. It is not capable of showing sensitivity to specific aircraft, sights, evasive spectra, tactics, etc. which would change the modeled characteristics. Details of the model mechanics are included in Reference 9.

SECTION III

AIMING ACCURACY

INTRODUCTION

In trade terminology, the predicted-impact-point/sight-cue is called the pipper. Some sights use an open cross hair where the gaps in both the elevation and traverse lines subtend about 10 to 20 mils, centered about the intersection point. The logic of the open cross hair design is that the gap does not occlude any part of the target such as its control surfaces which can signal change of maneuver. The pipper of the most common designs is a 2-mil diameter dot. Centered about the pipper, an outer ring, usually solid but sometimes composed of a number of diamond or triangular-shaped symbols, subtends a fixed diameter of 50 mils or varies in diameter with ranging inputs to match the pilot-inputted estimate of the target's wingspan or the pilot thumb wheels to match wingspan which estimates range. Some sights include an inner ring (usually broken) of about one-half the size of the outer ring which can be used as a gauge of tracking quality; a range bar which expands the width of an arc of the outer circle in a clock-type fashion or runs from the pipper or specific point on the outer circle on a specified diameter or provides a line gauge of about one diameter length along one side of the circle; roll tabs for horizon reference; and/or a fire point cue, signalled by blinking or a line running from the pipper to the undamped sight solution as an indicator of sight solution accuracy/damping. The collective set of symbols is usually called the tracking or sight reticle. Most designs include a caging switch. When caged, the sight reticle should superimpose the gun cross which may or may not be visible. When visible by electronic/optical generation or combining glass etching, the gun cross is usually closed cross hairs of about 20 mils subtense. The gun cross is the gauge for gun harmonization. The purpose of caging the sight is to avoid the distraction of a bobbin sight reticle during conversions, in addition to harmonization/boresight checks.

Pipper positions with respect to (wrt) the aimpoint/target-center can be directly reduced from gun camera film. The time history, usually plotted in an elevation-traverse plane that is target-centered and parallel to the associated sight axes, is called the (tracking/pilot) aim trace. This brings up the ambiguity of the term, aim trace, which is also used to define where the gun is actually shooting, neglecting ballistic dispersion, of course. The gun aim trace which AFATL calls the fireline to avoid ambiguity is the resultant factor which determines hits or misses. Unlike rifle shooting at fixed targets where boresight and ranging errors can be calibrated in the operator's head, there is considerably more complexity in the relationships between tracking aim traces and firelines with aircraft lead computing sights. In addition to the time-varying simultaneous solution of future target and bullet positions, the sight includes an equilization/stabilizing transformation between the gunline and sightline which is necessary for pilot controllability; i.e., such that the pilot can fly the aircraft so that the pipper will either superimpose or at least cross near the aimpoint.

As in other processes where error is not directly assessable, there are the supershooters who score well in comparison to others. Rationalizers claim that the supershooters have figured out the magic of the sight, that is, knowing how to spot the sight. If this were true, they would be aiming the gun, rather than the pipper. All indications from gun camera film analyses are that pilots track with the pipper. Accordingly, the aim trace used subsequently in this report refers to pipper-target relations unless noted otherwise.

One important fact and a corollary can be associated with the aim trace. The fact is that the pilot considers the quality of the aim trace to be the results of his (control) efforts. The corollary is that the pilot considers misses to be his or the sight's fault, according to whether the aim pattern (trace plus ballistics dispersion) misses or crosses the target.

UPDATE

Major innovations in gunnery assessments have been achieved since the original drafting of this report. They, including further refinements, are anticipated to be documented in about 1 year with their use reducing the AIMVAL/ACEVAL Gunnery Data Base. Accordingly, this subsection has been added to identify them and their potential impact with minimum revisions to the remainder of the report. The major portion of the original drafting of this section is included in the Background subsection.

It is noted that Combat Hassle reductions and reduction techniques have evolved over an interim that is approaching a decade. The innovations, specifically the Computer-generated Tracer Evaluator (CTE) concepts which provide accurate direct-assessability of the formerly unknown dynamics between sightline and gunline, are relatively new. Accordingly, assessments of data bases for which they have been available have not been as extensive as those for Combat Hassle. It is noted that some of the insight discussions in subsequent sections are based on Combat Hassle reductions, while more recent data bases have larger and more linear aim traces. Thus, while the technique is still correct, the driving functions will obviously be different.

A Butterworth filter has been programmed that removes the high frequency reader errors and vibration modulations of gun camera film readings/data without significantly changing the actual characteristics of the aim trace. A digital/Z-transform mechanization of the inverse sight transformation has been developed. Though subject to initialization errors that prevent assessment of exact location, it provides fireline characteristics such as shapes, magnitudes, and rates for specific pipper data. Since the gunline-to-sightline transformation is primarily a lag, the inverse is essentially a differentiation. Thus, it occasionally blows up for very noisy inputs. However, these cases are very easily spotted in the plots. Feeding the pipper readings through the Butterworth filter greatly reduces this sensitivity. The inverse transform technique was developed to reduce fireline

characteristics for those conditions where only gun camera film is available and as an interim until adequate data bases can be developed using the CTE. While the CTE requires flight instrumentation, it generates accurate fireline information, assuming that the gun is harmonized. Estimated accuracies in the 1 or 2 mil area have been confirmed for the airborne CTE by gun camera filming of tracer rounds.

Reductions have been made for a firepoint cue of one of the newer sights. The cue indicates error magnitude and direction of the damped pipper from an undamped one. Due to observed inordinately high dynamics, the accuracy of the cue is suspect. However, further analyses of CTE-instrumented tests are necessary before accuracy assessments can be made. The AIMVAL/ACEVAL trials should fulfill this necessity.

Statistical programs have been developed to reduce pipper, target, inverse sight-transform fireline, fire-point cue (when available), and CTE-derived fireline data for both gun-cross and target-center references. First, simple statistical estimators of means, standard deviations, root-mean-squares, maxima, and minima are derived for elevation, traverse, and radial positions and velocity measurements. Second, regressions are run on these statistics to determine whether encounter parameters such as range, angle-off, load factor etc., or their combinations influence the estimators. Present regression anlayses show no significant correlations for the scant data bases available. Larger data bases with better instrumentation and further examination of regression models and design of experiments are necessary to establish confident regression sensitivities.

Finally, additional data bases of the Yom Kippur War, Comparative Gunsight Evaluation Program, EXPO V (Simulator Tests), F-15 FOT&E, F-15 Gunsight Accuracy Tests, and the AIMVAL/ACEVAL Training and Trials plus additional liaison with users have provided new insight and categorizations of the aiming processes. All excepting the war and FOT&E bases included CTE-instrumentation.

The additional data bases and user liaison have substantiated the relatively low difficulty of former data bases and the necessity to categorize the aiming processes in accordance with the way the sight is being used. Of course, by design-intent, the LCOS pipper is supposed to be held on the target for the prescribed settling time of approximately 2 to 6 seconds before squeezing the trigger. Design-intent happens only on rare occasions; even in benign/cooperative environments or when the aware target is well beyond the effective gun envelope.

In operations research terminology, the design gunnery pass requiring near tail-on aspect was defined in three phases; coarse-to-fine tracking conversion, fine tracking, and breakoff. Attempts to apply these definitions to analytical processes result in many ambiguities in boundary criteria. This is especially true where attempts are made to apply the same definitions to non-design gunnery passes which may always have been and appear to be becoming the predominant situations.

Most authorities consider the tracking phase to be that portion of the aim trace where the error is less than some specified value. The value varies among authorities. Two typical values are 2 and 3 degrees; roughly 35 to 50 mils, respectively. This correlates to 35 to 50-mil 3-sigma boundary estimates for aim traces that are discussed later in this report. Other criteria such as trigger-on, trigger-off, and total time tend to provide insight to the arbitrary boundary criterion. In low difficulty cases, pilot discrimination has been observed that reduces aiming error statistics for trigger-on times. In higher difficulty cases, the boundary condition is exceeded in most cases. Specifically, in high angle-off (non-design) cases, the initial trigger-on error may be as high as 200 mils or more for ideal timing.

In former AFATL reductions of the presently-assessed low difficulty data bases, the 50-mil diameter sight reticle was used as a boundary criterion, because it simplified instructions to the film readers; i.e., pipper-to-target errors were such that target-center was within the outer ring. Reference to this criterion as stable tracking is not intended to imply fixed pipper-target error/displacement, but rather that the mean of the effort appears stable. Note that this is subjective. However, the availability of CTE-instrumentation makes this choice much more concrete; i.e., the longer time histories allow assessment that the pilot's mean effort has matched the turning rate with the mean within a boundary which could logically be chosen as the sight reticle.

Due to difficulty or inappropriate aim response or both, a significant number of passes occur where stable tracking is not achieved. These occurrences are characterized by turning rate matching (or nearly so) outside the reticle and a control response that results in the reticle passing over the target, usually one time. TAC representatives have called this dynamic tracking, which is possibly controls system terminology applied to unstabilized tracking. The error characteristics should logically fall somewhere between stable tracking and the slashing attack to be discussed next. Based on former observations, they were anticipated to be closer to those of stable tracking, while recent observations look closer to those for slashing attacks. Lack of sufficient data precludes confident estimators. However, the trend indicates that presently unquantifiable environment must be a strong driving function. Qualitatively, it is apparent that the latter data bases encompass more difficult environments. However, there is presently no regression structure to quantify base-to-base variabilities.

Finally, there is an apparent trend towards high angle-off shots, many of which are induced by the pilot to satisfy some tactical criterion such as minimum time to fire, sequential attacks by supporting elements, safe disengagement, etc. Formerly called Snap Shoot or Golden B-B attacks, they are setups, by a huge majority, rather than instinctive bursts as the target flashes through the windscreen from some unknown direction. Generally, the pilot sets up an overlead and holds it while his g builds up to 4 or 5 at an open fire range of about to 2000 to 2500 feet, presumably an adjusted

carryover of the nominal 1000 to 1500 feet firing range for design-intent gunnery and allowance for burst duration with high closure rates. Methods of maintaining visual contact for all but the last instant are too complicated for brief description. Similarly, some pilots hold g while others increase or decrease g during the burst. Pilot-preferred burst durations range from 1 to 3 seconds. Film reductions show trigger times from a fraction of a second to several seconds with a mean in the 1 to 2-second range. To be successful, the pilot must roll the target under the plane's nose at the last instant to match fireline and target directions and open fire while the target is still under the nose. Thus, the gun camera film shows that the target emerges from under the nose in a predominantly upward direction. A small fraction of slashing attacks occur with sideways target motion; i.e., the attacker matches his wing plane with the target turning plane. Occasionally, the attacker will roll opposite to target direction which has been sometimes called the inverted slashing attack. Cursory analyses of slashing attacks show error statistics which are a magnitude or more larger than those for stable tracking plus a bias due to predominately late trigger pulls. There are already a number of proposed sight modifications/concepts to improve accuracy. Their RDT&E will undoubtedly occur over the next few years, indicating continuing accuracy analyses. If present trends continue, adequate data bases for both slashing attacks and dynamic tracking should be available in the not-too-distant future.

BACKGROUND

The aim trace statistics that were formerly used in DATAM-I were derived primarily from extensive analysis of over 170 simulated gun firing passes from Combat Hassle flight test experiments, conducted in 1967-1968. Although this simulated combat between F-4Ds, afterburner thrust capabilities of one of the two combatants was restrained in four test phases from none to full. Thus, the results can be interpreted as those from a variety of engaging aircraft. The magnitudes and trends of reduction of approximately 25 Israeli combat-gun camera film passes and 600 EXPO manned-simulator experiments/runs appear to corroborate the Combat Hassle data base. It is noted that the EXPO experiments covered a variety of sights. Sighting statistics do change with sight type.

A few limitations and deductions about the gun camera film reductions and simulator experiments seem noteworthy. First, the film analyst cannot deduce the status of the cat and mouse game leading into or from the filmed aim trace, such as countermoves, counter-counters, missed firing opportunities, etc. Manned simulator experiments do show all valid firing opportunities, but time/expense has precluded all but the final conversion and firing phases. In these experiments, target maneuvering capabilities are drastically constrained by necessity to provide reasonable chances of obtaining firing opportunities; i.e., drastic target maneuvering in the terminal gunnery phases is beyond the response capabilities of fixed forward-firing gunnery. Additionally, all simulations in flight-test and simulators lack realism, especially the life or death stimuli of real gunfire. Further,

the best pilots are usually assigned as test subjects, possibly as a reward for their excellence. Second, Combat Hassle target evasive actions were mostly moderate-g horizontal turns, a half dozen or so low-to-moderate evasions, and about 3 or 4 of what might be considered high evasion for that aircraft. Further, there were only a couple of instances where radar lockon was achieved. The 1500-foot range, assumed by the sight when no radar range is available, resulted in a relatively stiff reticle for the predominantly long ranges with a nominal in excess of 3000 feet with an approximately normal distribution between 800 and 5500 feet. While there were a significant number of high target aspects including a few in the forward hemisphere, accompanying long ranges precluded high sighting dynamics. Accordingly, confidence in the aim trace statistics must be limited to low evasion spectra. Finally, aim trace characteristics were highly variable under seemingly similar encounter conditions. While attacker signatures including concentration, method, and initiation are obviously important, the unknown or pilot task-to-task variability seems to be the largest influence. It appears that guesswork can make or break a successful engagement.

Before describing the salient characteristics of aim traces, one important aspect needs clarification. DATAM-I models firelines, not aim traces. Thus, analysis of aim traces should be kept in perspective; i.e., a direct measure of pilot task performance and a basis for definition of fireline characteristics when direct measures are not available.

Aim traces show two qualities which simplify the methods of analysis. While variable from trace to trace, the rates along a given trace are fairly constant over time intervals that correspond with nominal gun bursts. The loops along the traces that could indicate multiple crossings of the target are negligible. Thus, the actual shape of the trace is not very important, but rates along the line define target crossing times.

Reference 5 shows the raw data average rate of the pipper wrt the target to be about 25 mils/sec, while the smoothed/draw average rate was about 7.3 mils/sec. The average of the 12 close range cases (0 to 1500 feet bin, actually 800 to 1500) is 41 mils/sec. Eliminating one questionably high rate, the average is 25. Dynamics of the tracking task are inversely proportional to range; i.e., the shorter the string, the higher the frequency which would be expected to cause tracking rates to be proportional to dynamics. Design of Combat Hassle experiments were directed to examine the effect of thrust capabilities on conversion. Gunnery tracking documentations were a secondary objective. With well over 50 percent of the cases outside the specified gun envelope of inside 3000 feet range and 30 degrees angle-off, and well over 95 percent with no significant target evasion, it seems apparent that extreme caution must be exercised in interpreting the indicated trends. Thus, while a pilot normalization of the task can be interpreted from Combat Hassle analyses, additional bases are considered necessary for an acceptable level of confidence.

Obviously, the raw data rates include both reading errors and camera and sight vibrations. Review of the smoothed data shows that the groupings used to smooth the data flattened the major peaks and wiped out intermediate variations which were obviously neither reading errors nor vibrations. Accordingly, the draw analysis data are not considered accurate. Based on the 6 to 7 mil range of the standard deviation and the aforementioned constant rate along the line, the calculated rate would be between 20 and 24 mils/sec. Accordingly, a nominal rate around 20 mils/sec would appear reasonable.

Three other distributions of Combat Hassle aim trace characteristics were analyzed: the average/meanpoint of the aim errors (AAE), the closest points of approach (CPA), and spotting. Recalling that aim wander is measured wrt the AAE, collective consideration of wander and the AAE gives an indication of the timing/phasing of trigger pulls with the oscillatory nature of the aiming effort. The salvation of disturbed reticle sights is the inability of aim efforts to achieve and hold good aim, substantiated by the anecdote that the safest place for the target to be is under the pipper. Sometimes, during all the wandering, the bullet stream crosses the target. Addition of CPA to wander and AAE provides a measure of the directivity of the aiming process. Assuming perfection of the other areas and no interaction, the important part of the aim trace is the CPA and close proximities. As used here, spotting is not the shoot, observe and adjust process of the less dynamic field/naval artillery problems. It's the "Kentucky Windage" where the shooter adds/spots some angle onto the sight solution to correct for various factors that he knows or suspects that the sight does not handle right.

Attempts were made to check the sensitivity of the rms value of AAEs as a function of range, angle-off, attacker/tracker load factor, target evasiveness, target turn severity, wander rate, and tracking quality. AAEs were in the range of 10 mils for poor tracking (target-center outside the inner reticle) and high wander cases. Almost always, poor tracking indicates high wander and vice-versa. For good tracking (inside 5 mils)/low-wander, the AAEs were about 5 mils. AAEs change proportionally by a mil or so inside this range for low to high increases of the other parameters. Small samples in large bins in addition to aforementioned cautions leaves little confidence in the measured sensitivities. It seems factual that 5 mils looks like the lower bound of the rms value of the AAE distribution, and this will double, maybe quadruple, as difficulty increases. Again, pilot variability as categorized by tracking quality is clearly the dominant factor in this data set.

The rms values of the CPAs were also analyzed as a function of these variables with similar findings. The lower limit looks like about 2 mils. It was about 5 mils for the more difficult Combat Hassle cases which could indicate an upper bound of 10 mils or so for combat/forced conditions.

Various authorities, both users and system and component manufacturers, have proffered various and sundry techniques of spotting the aiming effort

to maximize hits. Some suggest adding a number of pipper diameters in specified directions for dart firings and specific target evasive actions, while others suggest crossover anticipation schemes involving time-of-flight estimations. In general, pilots cannot handle it; therefore, they don't like it. While it is manageable for dart firings and other highly controlled experiments, they invariably think of the pipper as the actual firepoint when under the duress of air combat maneuver tracking and firing. Nothing frustrates them more than getting the pipper on the target and not registering hits.

Combat Hassle data were also analyzed to determine whether pilots were spotting the sight solution. The analysis showed that the pipper was below the target about 69 percent of the time which should be expected from both the following nature of the tracking task and breakoff. Otherwise, the quadrant distribution of aimpoints was fairly even. These statistics plus subjective viewing of the films indicate that the pilots were not intentionally spotting the solution in the Combat Hassle experiments.

In concluding the discussion in the area of aiming accuracy, it is noted that without some form of pilot sighting error compensation, the results that could be computed from the aim traces without other errors is the best that the system can do. Also, it is the pilot's interpretation of what is or should be going on. DATAM-I does not generate such results in its present format. This could be of significant value to show how well the pilot does the interpreted job and the influences of sight/estimated-solution errors, target uncertainty, and/or interactions. The pieces of the problem and how they interact could be quite revealing.

SECTION IV

SIGHT ACCURACY

BACKGROUND

Gunnery estimates became a science, primarily through the efforts of Siacci in the late Nineteenth Century, when relative motions were slow. That is, the future position of the target was not much of a problem; and artillery pieces could be layed with deadly accuracy, even at long ranges requiring Coriolis corrections.

High mobility of the Twentieth Century forced the estimates to compromise in many cases in order to handle future target position estimates with state-of-the-art technology. The speed ring sight of World War II vintage is a good example. The advent of jet engines and guided missiles in that era posed a much greater problem.

Following World War II, considerable effort was directed to develop sights/estimators which would be effective against these more mobile threats. The automatic director sight was the obvious ultimate answer for free-flight weapons, but automation technology was in the infancy stage. Sensing/tracking and computational mechanizations were encumbered by the reliability of hard tube electronics which was barely advanced from the original Fleming Valve. Servos were first cousins of the Stewart-Warner classic, and filter theory was essentially limited to smoothing and memory networks. The heavy and bulky packaging, especially electro-mechanical components, caused avionics (aircraft electronics) to lag behind the state-of-the-art in other fields. Solid-state avionics with sophisticated best-estimator and error distribution filter theory is just beginning to impact this area, and is still understood by only a select few.

Before the development of the automatic director system, the optical sight later called either the manual director or LCOS, was the principal basis of fire control estimations. It became the backup mode to be used when the automatic director system broke down which was most of the time in these early stages. Thus, adaptation of the LCOS as the gunsight for weight-sensitive fighter aircraft was a natural during this era.

In lieu of driving the gunline to lead the line of sight (LOS) by computations derived from LOS tracking variables, the LCOS used gunline motion to estimate a lead angle which is added backwards/disturbed from the gunline. While regenerative in nature, this backwards solution of the fire control problem can address all aspects of fire control as well as the director if the disturbed reticle can be held on or very near to the target. The eyeball director system has been coined by promoters of this concept. It works quite well from stable tracking platforms in situations with low

dynamics such as fighter-against-bomber attacks where nominal conditions are easily attained. When automation assistance is needed to stabilize the trackline, it simply makes sense to convert to the automatic director approach, avoiding the regenerative nature of the backwards solution. Present LCOS systems dampen their solutions to provide a flyable reticle which does extend the acceptable range of sighting dynamics at the expense of causing errors between the presented and actual lead angles.

Almost all current fighter aircraft use the LCOS-type sight for air combat. Accordingly, the major impetus in this report is placed on the accuracy/error of this sight to perfectly solve the estimate.

In addition to assuming/estimating that the target is in some state and will continue to remain in that state for a specific time interval, some sights especially the LCOS assume nominal conditions for some of the fire control variables, rather than instrumenting and accounting for them. One rationale given for ignoring some variables is that the 3-sigma bound of aimpoints is a circle of 30 to 50 mils radius about the target center, so why worry about an error source whose rms value is a couple of mils or so. The obvious error in this rationale is the loss of aim trace CPA characteristics in this hopper statistics viewpoint. Assumptions on both target states and other fire control variables can cause ambiguities in definition of sight/solution accuracies. In these discussions, sight accuracy assumes perfect angular tracking input and perfect target state matching with the estimate. Input errors of noninstrumented variables are simply their perturbations about the assumed nominal.

In the following discussions, sight accuracy is covered as harmonization/boresighting, input, approximation, and mechanization errors.

HARMONIZATION/BORESIGHT ACCURACY

While guns do have tendencies to change boresight during burst stressings, the change is generally in the mudlevel of boresight mensuration accuracy and is therefore ignored in error analyses. Slight finger pressure on the combining glass will change the sight boresight reticle alignment by about 1 mil. The influence of 4 or 5 gravitational units should be considerably greater. Changes of pilot head/eye position can cause a couple of mils change in the direction of the boresight axis. For analog mechanizations of the LCOS utilizing the lead computing gyro, the pipper is a light-mask reflection off a mirror that is driven by electro-mechanical servos which displace the mirror alignment to input elevation and traverse lead angles. Thus, in addition to the basic optical alignments and fidelity, there are gear/backlash tolerances and all of the servo balance, linearity, and temperature et al sensitivities. Gun camera films have shown sticky, stepwise pipper motions which users have confirmed seeing in airborne operations of these hermetically-sealed, life-time-unserviced sight units. Head-Up Displays (HUDs) should help, but they have similar problems. Further, the airframe flexes differently under landing gear support, boresight alignment

jacks and the various aerodynamic loadings in flight. Flexure has been calibrated for side-firing gunships and one of the newer USAF fighters for air-to-ground gunnery. There is no confirmed compensation for air-to-air gunnery. In the dry/nonfiring boresight procedures, the sight is aligned wrt the airframe by means of a peepsight that is screwed into hard points that are located near the middle of one side of the fuselage. The 1000-inch standard is usually white-background-painted plywood with black-painted reticles for peepsight, gunsight, gun optical boresight, and gun mean-point-of-impact alignments. Jury-rigging of various forms of standards are common practice. Problems abound with establishing vertical and horizontal/level plane alignments of both the standard and the aircraft. Because the gun is not generally aligned to the level/water plane of the aircraft, the aircraft must be jack-tilted to level the gun or the standard must be moved and cocked to compensate. Slop and tolerances of both the peepsight and the elbow sight, that are fitted into the muzzle end of the gun barrel, are well known problems with unknown error distributions in addition to quadrature correction uncertainties of the elbow sight. Technical Orders that specify harmonization procedures usually allow 3 to 5 mils error per axis without requiring adjustment/readjustment. Wet-firing boresights are rarely performed and when made, only one or two short bursts are fired on a range that is not instrumented to properly account for local wind effects. Mean-point-of-impact variations of nominal bursts are unknown for even the type of aircraft installation. This causes a grey area of one-mil or more to start with. Variations with short burst length are also unknown, but should be expected to be larger. No documentation on harmonization is required or kept. One local check of a squadron of the 33rd TFW at Eglin AFB, Florida showed measurements of about 3 mils rms on dry boresight of the best. Including the four aircraft with errors over ten mils, the rms was about 6 mils. In the mid 1960s, the Fighter Weapon School at Nellis AFB, Nevada best-guessed these errors in the 3 to 5-mil rms ballpark. Because these users are only familiar with the measured errors and not the basic uncertainties, a 4 to 6-mil rms value is proffered.

INPUT ERRORS

Sight inputs include variables to estimate both the target and bullet flight paths for intersecting solutions. Target path estimate inputs will be addressed first, followed by those for bullet path estimates. However, the estimate is the simultaneous solution of both paths. Accordingly, they interact and completely separate treatment is not possible.

Target path prediction requires inputs of range and angles (polar coordinates) and their derivatives. It is noted that while transformations to Euclidean/Cartesian coordinates may assist some to better envision the problem, the accuracy of polar coordinate solutions are mathematically identical. Range and angles define the zero-order state, present position. Range is either an input from the onboard radar or assumed to be a nominal value; e.g., 1500 feet. While some improvements have been made, the onboard

radars of current fighter aircraft are still primarily designed as missile directors which compromise their already inherently-limited capabilities in air combat gunnery. Influential user groups continue their insistence that they want a sight system that does not require range inputs even though simulations (Reference 8) show about a half order of magnitude reduction in expected hits. If not the largest, lack of range input is one of the largest accuracy parameters in the sight solution. Selecting mid range of sight solution limits with the above mentioned nominal range for insight/appreciation into the influence, the sight would compute about 40/30 mils long/short for 1000/2000 feet target range, based on the resultant inaccurate time-of-flight calculations. Note that this affects both linear/velocity and second-order/acceleration terms. These errors fit into the most stringent degradation category, bias.

The LCOS also uses range rate from the ranging input. Based on 1 percent rms linearity, the accuracy due to this parameter for nominal closing rates should be further down in the mudlevel wrt steady-state elevation and traverse angular rates that are discussed next.

Based on the premise of perfect tracking and on the fact that gunsights solve this estimate in the relative frame of reference (gunstation coordinates), there are no angular errors; i.e., the target is under the pipper. The lead computing gyro of the LCOS is a fairly accurate instrument for measuring steady-state vertical and directional plane angular rates. Due to instrument tuning and quality control, the rms bias is estimated to be about 0.5 mil/sec, while the rms value of its linearity is estimated to be about 1 percent. Thus, even for an attacker load factor of about 6g which would cause 200 mil/sec rate, the rms linearity error would be only 2 mils for 1 second time-of-flight. Though in the mudlevel overall, it should not be ignored. Eddy cup feedbacks are known to be noisy. Based on this, the dynamic accuracy might be a factor or so larger than static accuracy.

While roll rate has been sensed and included in some LCOSs such as the A-1, it is not instrumented/included in most currently operational LCOS systems. Depending on LCOS mechanization, Air Force Academy studies of static sight/estimate accuracies have shown errors ranging from 11 to 67 mils for about 12 degrees roll rate in a banked 4g pullup against long air combat gunnery range targets. The lower range of these errors was for proffered sights which computed roll rate effects. It is also noted that the proffered rate inputs would come from a rate gyro triad-package of good flight control quality; i.e., about 1 percent rms linearity.

The LCOS does not use higher derivatives of polar coordinates than those indicated in its estimate. Thus, they fall into the area of estimate uncertainty. However, some LCOS systems use normal acceleration in a matched-g-estimate prediction scheme. The quality of accelerometers may vary by type of aircraft. To appreciate its influence, consider 1 percent rms bias and linearity effects. For 1 second time-of-flight, the rms bias term would cause an rms error of less than 0.1 mil. With 6g, the rms linearity

term would cause an rms error of about 0.5 mil. Thus, for such accuracy, steady-state error due to input accuracy of this sensor would be in the mudlevel. However, accelerometer outputs are notoriously noisy and must be filtered before their use in fire control. The delay due to lag is incidental to most design-intent engagements, but it can cause appreciable error terms with realistic aiming processes.

Having covered the input errors of the target path estimate, it is noted that it assumed perfect prediction of time-of-flight for cases with range inputs. It is also noted that there is no assumption in the estimate that the instantaneous orientation of the gravity vector will influence the path.

To accurately predict the bullet path from any gun, it is essential to know the status of the firing platform, the orientation of the gun wrt the platform, gun and ammunition characteristics, and the characteristics of the medium along the trajectory.

Obviously, instrumentation of the medium beyond the launch platform is not possible in air combat gunnery. Thus, simplifying assumptions are necessary; i.e., both attacker and target are in-equlibrium/moving with any motion of the air mass. Gust spectra with an 8 ft/sec rms value will cause about a 2 mil change in bullet path direction, but it will return to about its original direction at the end of the nominal 0.1 second duration. Thus, bullets affected by the gust will be moved about 1 foot upwind from the direction of the gust. The large inertia of the aircraft results in very little weathercocking and small accelerations in the opposite direction. Gust effects are ignored in bullet path estimate computations. Similarly, wind velocities that can be appreciable over altitude differences of over a few hundred feet are ignored. Note that bullet aerodynamic jump into the wind and aircraft equilibrium/floating with the wind are in opposite directions. Maneuvering aircraft are rarely in equilibrium with the wind, but this is an uncertainty of the estimate which is covered in the next section.

While a prime factor in long range artillery, the inaccuracy of the air density measurement inputs to bullet path estimates is a second order effect for air combat gunnery ranges.

A major argument exists within the community on the effects of crosswinds; i.e., angle of attack and sideslip. Simplicity advocates use small angle approximation derivations to show that the aerodynamic jump angle caused by crosswinds cancels out, while the other side shows that without the small angle approximations, the aerodynamic jump angle is a reality that definitely influences the path of the bullet. The simplicity advocates use bench accuracies of the angle of attack sensor and claim coordinated directional flight (in air combat maneuvering) to circumvent the fact that there are no sideslip wind-sensors on operational aircraft. The USAF Sixshooter Program at Tyndall AFB, Florida in 1973 indicated a sideslip of about 1 degree for the relatively benign maneuvering in that program. A USN air combat simulator study showed an rms value of about 1.5 degrees sideslip

for that program. Angle of attack sensors are accurate to a few tenths of a mil, but local airflow variations are estimated to be about 2 to 4 degrees rms in accelerated flight. At about 4 mils/deg sensitivity to crosswinds, these are major input error parameters to bullet path estimate accuracies.

Using the 2 percent burst-to-burst muzzle velocity rms variation, this causes about a 2 percent error in time-of-flight. For mid-range lead angles (125 mils), this causes a 2.5-mil error which cannot be ignored. Aircraft velocity sensor accuracies may reduce the overall launch velocity uncertainty slightly which would have a similar impact on this error.

Angular rate of the Gatling gun barrel cluster causes a throw to the exiting projectiles that is compensated at 1200 feet range by canting the barrels both inward and tangential to the direction of motion. With the compensation, this is not a major error; but it cannot be ignored.

Gunpowder has a temperature sensitivity coefficient of 1 ft/sec/°F. Loadings are based on nominal muzzle velocity (3350 ft/sec) at ambient temperature, about 60°F. Cold soak temperatures at altitude are about -40°F. Ram air temperatures range around 200°F, but their durations during gun gas purging are short. Accordingly, the airborne muzzle velocity may be as much as 100 ft/sec lower than ground firings. Coupled with mid-life barrel wear, this could cause the projectiles to be 10 mils behind the target for mid-range lead angles. The statistics of the uninstrumented powder temperature are not known. Obviously, the mean should be treated as a bias term, while the rms value should be treated as a systematic error. Barrel wear statistics are also unknown, although muzzle velocity variation with barrel wear is. Variations of burst length and time-sequencing of bursts have significant influences on barrel wear. Operational records of these events are not kept. Thus, the best method for analysis is to run separate phases for new, mid-life, and worn-out (3100 ft/sec) barrels, treating the wear-related muzzle velocity as a bias. The influence might be used to determine the necessity for documentation.

Orientation of the gun wrt the platform is a fairly simple transformation for a fixed-gun; i.e., gun elevation and train/traverse/azimuth angles and 3-dimensional translations are fixed. Interactions of gravity and parallax on the bullet path are also fairly simple, assuming that the platform is level. When the platform is not level and direction of gravity/verticality is not instrumented, assessments are not so easy. Recall that the gun is harmonized to cause the bullet stream to be coincident with the gun-cross/harmonization-point which is usually at 2250 feet range during harmonization where the platform/aircraft is either level or cocked in the pitch plane only. Consider first a gun muzzle about 6 feet lower than the sight. Parallax is about 2.7 mils and gravity drop is about 4.5 mils for a total of 7.2 mils. When banked at 90 degrees, simplicity advocates claim the target and bullet are falling due to gravity at the same rate. But this leaves 4.5 mils above parallax correction in the aircraft vertical plane that is not compensated. Orientation of the gun wrt the platform is not

accounted for in the estimate. Stomping and holding opposite rudder pedals every few seconds has been expressed by pilots as standard defensive tactics when in the target role which is diametrically opposed to the claim made by the simplicity advocates. However, this can be covered under estimate uncertainties. Accordingly, while ignoring orientation of the vertical may be irritating to the exacting in that it truly causes bullet path estimate errors, it can be accounted for in one area or the other as long as the basis is known. Uninstrumented parallax should be considered a sight input error.

State of the firing platform is the last factor on bullet path estimates to be discussed. Uninstrumented verticality has already been mentioned in both target path estimate and gun-platform orientation input error discussion. Pitch and roll define verticality, while heading as well as position is covered by the relative frame of reference and perfect tracking premise. Roll was covered previously concerning gun orientation. Uninstrumented pitch attitude would be catastrophic to field artillery, but it is a second order effect in nominally shallow turning planes and short range interval of air combat gunnery. If present emphasis on vertical plane maneuvers continues, its effect on bullet path estimates should be included. Angular rates of the platform affect the bullet path throw in an identical manner to rotation of the barrel cluster. With 20 to 30 foot-lever arms from the aircraft cg, these influences which are not included in the estimate must be considered as uncompensated errors.

The air data computer (ADC) or central ADC (CADC), as it is usually called in modern aircraft, uses sophisticated compensation schemes to provide a fairly accurate measure of true air speed, aircraft motion wrt the air mass, for unaccelerated flight. About 1 percent rms error is a fairly confident estimate, compared to the 0.5 percent error of ground-track velocities that are provided by very expensive Doppler velocity sensors. But, accuracies degrade in accelerated flight. In certain geometries, the error may exceed the 2 percent accuracy of burst-to-burst muzzle velocity dispersion.

Both linear and angular velocities of the platform affect an apparent (ballistics) curvature of the bullet path. Of course, they also affect an apparent motion of the target. On its basic premise of matching LOS rates, the disturbed-reticle sight uses aircraft vertical and directional plane angular rates to predict the apparent target motion. Note that the estimate assumes constant velocity. Thus, for constant velocity, both target and bullet path curvatures are predicted for these rates. However, bullet slowdown, gravity drop and platform translations are factual. An estimate of ballistics curvature is made that uses several simplifying assumptions which have limited validity and neglects sideslip and gravity orientation. Sideslip is a manifestation of lateral velocity/acceleration platform-motion, similar to alpha/angle of attack in the vertical plane. Again, ambiguities can arise over where the errors belong; i.e., based on the assumptions, the errors are negibile. However, the assumptions are erroneous to various

degrees. It is proffered that those factors involving ballistics should not be categorized under uncertainties. Therefore, uninstrumented sideslip and verticality should be considered input errors, while the errors due to simplifications definitely belong under sight approximations.

Finally, time-of-flight is derived from usually an iterative solution of the ballistics triangle of the estimated solution. Ranging input error statistics can be easily misinterpreted. Design specifications are usually written by the manufacturer and are therefore rather loose for his protection against legal actions. Quality control specifications are similarly handled, but will reject a small percentage to assure meeting other qualifications. Ranging accuracy for missile directors are usually specified as about 75 feet plus 4 percent of range. If this is interpreted as a 3-sigma (99.7 percent) level, which it should be, this error ranges from about 1 percent at 1000 feet range to a few tenths of a percent at 3000 feet range.

APPROXIMATION ACCURACY

United States Air Force Academy studies of static sight accuracies show about 5 to 10 mils average error for various LCOS mechanizations to a proffered tracer standard that portends to accurately account for all ballistics parameters. This very limited study modeled the LCOS algorithms in a large digital computer with assumed perfect inputs. The results were obtained for estimated flight paths of 4g level/45-degree-bank/pullup maneuvers at 3000 feet range with constant velocities of either 600 or 800 ft/sec. Including the basic uncertainty of ballistic standards and the accuracy of the tracer standard, a 2 or 3 percent approximation accuracy could be proffered; but more extensive studies of this type are necessary before any level of confidence can be placed in approximation accuracy.

These errors obviously encompass approximation accuracies; i.e., truncated series, equivalence approximation, etc., including those that were noted previously in ballistic curvature discussions. Results show about the same level of accuracy for level and pullup estimated maneuvers. Further breakdown would be necessary to determine whether the inaccuracies were caused by uninstrumented parameters or sight algorithm approximations.

MECHANIZATION ACCURACY

This factor can be easily envisioned as inter-instrument/manufacturing repeatability or quality control. With the accompanying scatter graphs that are submitted with some manufacturers sight accuracy claims, it is suspect that these are manufacturing tolerances around the company-adopted standard, the production mean. Whether HUD or electro-mechanically driven mask, the pipper presentation accuracy has been estimated as 0.5 mil plus 1 percent of lead angle output by the computer. The lead computing gyro or rate gyro package accuracies were included under input errors. Lead angle output from the computer algorithms is estimated at about 2 percent rms of the lead angle for analog mechanizations and about 0.5 mil rms for digital mechanizations, primarily from analog/digital converters.

SECTION V

ESTIMATE UNCERTAINTY

GENERAL

The final area to be discussed before considering interactions is the uncertainty of the estimate. Revered and/or associated with the mystique in some circles, target uncertainty is simply the inability to predict exactly what an uncooperative target will do in the future. Certain assumptions of the estimate such as considering both aircraft to be in coordinated, constant velocity flight have been previously addressed. Variations of the attacker from assumed/estimated conditions also contribute to estimate uncertainties. However, variations of the target are by far the dominant influence. Accordingly, the following discussion is directed to address prediction schemes and resultant uncertainties.

Displacement from a body's expected/estimated position is a direct measure of uncertainty. All LCOSs assume constant velocity. Until near the end of 1972 these sights also assumed unaccelerated/constant-inertia/first-order flight. With this basis, the following subsection shows past ways for visualizations and some restrictions and/or limitations of these ways to illustrate the principles of uncertainty.

THE CORNUCOPIAN CONE

To dramatize the potential impact of target uncertainty on the prediction problem, it has been common practice in the past to show a Cornucopian cone about an instantaneous velocity vector. The line on the cone surface made by a plane encompassing the velocity vector was simply computed as the second order term, the acceleration multiplied by one-half of time-squared. Note that this simplification disregards velocity variations along the line which would result from constant velocity along a curved path or varying velocity. Also, the cone has usually been constructed to be symmetrical about the constant-inertia velocity-vector. Due to human tolerances, aircraft acceleration capabilities are not symmetrical about the fuselage reference line: but sights don't measure target attitude, either. Thus, symmetry was sometimes explained as bounding limits, based on unknown or random differential attitudes of attacker and target. Other times, asymmetry was shown based on various and sundry target maneuvering schemes; e.g., g-buildups and programmed roll rates. Note that any time-sequences should be considered variable with burst initiation/mean-point/termination.

Aircraft acceleration along the thrust line is sometimes limited by the thrust-to-weight ratio (T/W). Past T/W has limited level flight accelerations to a fraction of a g. However, decelerations from speed brakes and

flat-plating can be very high, many g. Continuing for the moment with the constant-inertia/center-line initial condition, this consideration along with diving flight paths and higher T/Ws changes the uncertainty region from the internal region of a normal plant wrt the velocity vector at some specified future time to an oblate spheroid.

The magnitude of the acceleration causing the surface of the cone has also been selected on the basis of various criteria. Some chose the maximum steady-state g capability of the target for a specified flight condition. Some aircraft might be limited to 3, 4, or 5g by this criterion. Others chose a human limit from 5 to 7g, based on blackout or other psychological factors which might affect continuing functioning of the mind. Still others chose the maximum steady-state MIL-standard, 7.33g. It is noted that the MIL-standard momentary (several seconds) g design specification is around 12g. Thus, a last ditch evasion could reach up to around 15g, possibly popping a few rivets.

The constant inertia basis should not be considered nominal for aware dogfighting. According to past tactics, a break maneuver (5g) into the attacker has been specified as the standard tactic. Higher performance aircraft will push this standard upward. Thus, the instantaneous velocity vector should not be considered to be either in the center or on the surface of the cone; and, uncertainties can be generated by rolling as well as loading/unloading.

ESTIMATES AND THEIR UNCERTAINTIES

Obviously, if the target were cooperatively forecasting its flight path, the path could be matched exactly by either a Taylor series or numerical methods so that there would be no uncertainty/error. Autonomous aware target control tries to be unpredictable when being fired at. Thus, the sight designer must select a best-estimate prediction scheme. The incremental form of the Taylor series is generally the basis of fire control prediction, written as:

$$f(t + h) = f(t) + hf'(t) + h^2 f''(t)/2! + h^3 f'''(t)/3! + \text{HOT}$$

where $f(t + h)$ = future state at increment, h, from present time, t

$f(t)$ = present zero-order/position state

$f'(t)$ = present first-order/rate state

$f''(t)$ = present second-order/acceleration state

$f'''(t)$ = present third-order/jerk state

HOT = higher order terms

There is no error if all states remain constant over the increment. Historically, anti-bomber sights have ignored all terms higher than the first-order state. Assuming the pipper to be held on target-center, the LCOS accurately measures the rate state.

Impressive gunnery results with essentially no gunsight spurred the development of an anti-fighter gunsight that estimates matched attacker-target accelerations. To get a feel for second-order influence, consider a half/one second future gunnery state to be 1500/2500 feet. For a constant 5g target, the ignored second-order influence is 14/33 mils for 0.5/1.0 second time-of-flight (TOF). Note that ignored prediction orders are bias errors, not random. Now, consider the acceleration match estimate. The match scheme will cause the same/double errors if the target unloads/reverses at the time of fire. Attacker judgment is still crucial to hold/initiate fire. Also, engagement geometry (range, angle-off) imposes accelerations on the attacker which do not necessarily match the targets. Additionally, it is noted that at high angle-offs where g is high, the majority of the second-order influence is into the attacker. To the author's knowledge, this is not accounted for in the sight equations. While further analyses are needed, a best guess of one-g rms mismatch is offered, 2.75/6.5 mils for 0.5/1.0 second TOF. Observing the magnitudes of second-order influences/states, one has to agree that the break, high-g-turn into the attacker, is a sound aim-spoiling maneuver against first order sights and is still fairly sound against matched-g-estimate (pseudo second-order) sights at longer TOFs. Finally, consider the jerk term. The target can load several g in a fraction of a second and can unload faster than load. However, net g is required for both displacement from present flight path and advantage maneuvering; i.e., rapid stick-pumping allows the attacker to settle in for a point-blank-range shot. Also, the jerk term has the $TOF^3/6$ coefficient. For 0.5 second TOF, 6g/sec jerk causes only 2.7 mils error. One experiment measured the rms of jerk at about 0.5g/sec. Thus, the jerk rms would cause 0.2/2.2 mils in-plane error for 0.5/1.0 second TOF. The important facet of jerk is out-of-plane effects. The target can usually roll about 90 deg/sec. Accounting for the attacker response lag, this not only directly rotates the second-order state, but also causes rapid changing of the first-order state which compounds the tracking problems with the regenerative nature of the LCOS which presently also ignores rolling terms. Reference the Air Force Academy study showing 11 to 67 mils error, due primarily to about 12 deg/sec roll rate.

Without careful attacker judgment, uncertainties can be appreciable. Until further analyses are available, a linear function of 10 mils/sec of TOF is offered for matched-g-estimate sights, based on an inverse relationship of target roll rate with TOF and attacker judgment. Note that DATAM-I computes the second-order term as a bias error to linear sights.

SECTION VI

INTERACTIONS

GENERAL

Former discussions were concerned with the major areas of the fire control problem. The following discussions are directed to describe how to put them together, including interactions, in order to properly assess fire-control/gunnery effectiveness.

When the target moves such that it displaces itself from the sight estimate, the attacking pilot changes his control efforts to follow, attempting to null the displacement. This change causes the sight estimate to differ which modifies the attacking pilot inputs. Meanwhile, the target's observance of this affects his subsequent actions. This Markhov-type chain of events has been mathematically modeled for gunnery as well as other mission phases, but only in a cursory manner. Proposed and programmed studies are in the offing to investigate the influence of such interactions on sighting and sight accuracies. That is, instead of investigating these accuracies for the condition where the target flies the estimate, this approach should define accuracies for the targets which do not fly the estimate. Considerable time and effort will be needed to determine the sensitivities of these interactions.

On the coarser level of present treatment, efforts have been made to transform the aim trace into the predicted/estimated impact plane. Thus, if the resultant accuracies and uncertainties of the sight are included, addition of ballistic/gun dispersion to the fireline/transformed-aim trace provides a model of the gunnery effort. Inverse sight transform, pipper, and track wander analyses of the Combat Hassle data base shows that on the average, fireline rates and magnitudes are about twice as large as those of the aim traces. A better insight should be available after reading the subsection that follows on dynamic errors.

Ballistic dispersion which transforms firelines to firepatterns will be addressed first. Envisioning of the firepattern is a powerful tool for the gun designer. Extent of and density/lethality within the firepattern influences the gun design problem. Getting the target within the pattern is another problem. From the pilot's viewpoint, ballistic dispersion is a cone, rather than a line, that the gun fires. Most envision this as a cookie-cutter circle, centered about the pipper and a couple or so pipper diameters across.

BALLISTIC DISPERSION

To the purist, ballistic dispersion is a measure of the variations about the mean line of departure (MLD) that are caused by imperfections of the

barrel, round, and muzzle-exit interface when the barrel is clamped to obviate any appreciative barrel motion. MLD is usually defined by the mean point of impact (MPI) in a set impact plane. With optimal design and selective matching/screening, tests of new single-barrel guns in controlled/enclosed environments have shown standard deviations of less than 0.1 mil. In this purest sense, ballistic dispersion statistics conform to a circular normal distribution.

A myriad of other factors can influence both dispersions of and about the MLD, i.e., asymmetric recoil mechanisms, free-muzzle whip, variable environments, standard production tolerances, multiple-barrel aimpoints, allowable wear, vibration, dispersion inducers, etc. Many are not random. The gun designer has varying degrees of control of these other factors. A good feel of M-61 patterns can be obtained from Reference 10.

The gun designer/user defines ballistic dispersion as the diameter of a circle that excludes/contains 20/80 percent of the gun pattern hit points, centered at the MPI. The gun designer also tests for variances of the MPI. Thus, good terms for these dispersions are proffered to be gun pattern dispersion and gun MLD dispersion. To the author's knowledge, gun MLD dispersion for the M-61/A1 is not documented for user aircraft or included in fire control error budgets. A best guess is one-mil rms. The impure ballistic dispersion definition is whole-community trade terminology, and therefore should be retained. However, the definition should be made clear to analysts.

DYNAMIC ERRORS

Dynamic errors are induced by the gun-to-sight transform which usually includes both lead and lag terms of pipper-target displacements. During conversions, these errors are usually in the tens of mils, because the damped sight cue lags the undamped lead angle by 20 percent or more. With conversion rates in the 50 to 100 mils/sec range, it is readily evident why some authorities proffer fire synchronizations to counter this lag.

In the former data bases, conversion blends into steady-state/fine tracking before firing commences. Pilots, being taught to hold the pipper on the target until the sight settles, indicate that they never achieve fine tracking in combat. However, combat gun camera films show that in most cases they have estimated the LOS rate, and pipper excursions about the target are within the proffered boundaries.

Spectral analysis of Combat Hassle data showed the average frequency of the excursions to be 0.5 hertz, i.e., a 2-second period. It is noted that many human factors studies show the operator response limit to be in the 0.5 to 1.0 hertz range. The frequency of the longitudinal plane short period mode of these aircraft is 0.5 hertz. Accordingly, pilot control imputs should excite this mode, causing it to be predominant. Before examining the nature of dynamic errors, other aircraft modes and their difficulty/

compatibility with operator response is offered for insight. The natural frequency of aircraft short period modes increases by about a factor of three, i.e., the natural frequency of the longitudinal modes is about 3 times higher than that for the directional, while the natural frequency of the lateral mode is about 3 times higher than the longitudinal. Then, generally speaking, the pilot can handle directional mode oscillations, but lateral mode oscillations are beyond pilot response capabilities. Actually, this is based on single axis inputs. Two axes inputs degrade this capability. Lateral, directional, and cross-coupling modes modulate lateral pipper motions, while longitudinal short period, lift, phugoid, and cross-coupling modes modulate the elevation pipper motions. Phugoid modes caused by varying velocity with pitch attitude have periods in the range of 20 to 30 seconds which are at most a slight aggravation. Periods of lift mode modulations of the vertical plane attitude are in the 6 to 8-second range which is about in the middle of the range where the pilot functions best. The essence of this paragraph is that the tracking task, at best, presses the response capabilities of the pilot; and, the natural frequencies of the airframe that are excited by the tracking control inputs cause complicated overall responses which make the problem more difficult.

The frequency-domain (s-variable) transfer function for the gun/aircraft pointing angle (THETAG) is:

THETAG(S) = THETAS(S)*(1 + (1 + SDF)*TN*S)/(1 + SDF*TN*S)

where THETAS = sight pointing angle

SDF = sight damping factor

TN = sight sensitivity, TOF for TOF rate = 0

(Note: Fortran form has been used to ease typing load, i.e., no Greek letter symbols. Asterisks are used for multiplication sign). Neglecting a transient term that disappears rapidly, the time domain (T) transfer function for a sinusoidal THETAS is:

THETAG(T) = A*B*((C**2 + E**2)/(D**2 + E**2))**0.5* sin (E*T + PSI)

where A = sight peak amplitude (in mils)

B = (1 + SDF)/SDF

C = 1/((1 + SDF)*TN)

D = 1/(SDF*TN)

E = sight angular frequency in radians

PSI = gun angle phase lead

= ATAN(F) - ATAN(G)

F = E/C

G = E/D

ATAN = arctangent of the argument

The following examples of this influence are derived for the Combat Hassle average period. For a SDF of 0.25, the phase lead is 42.3/37.6 degrees for 0.5/1.0 second TOF. For a SDF of 0.4, the phase lead is 33.4/25.6 degrees for 0.5/1.0 second TOF. Gun angle excursions are a little over twice as large as pipper excursions for the longer TOF for either SDF. At the shorter TOF, gun angle excursions are about 3.2/2.8 times those for the pipper. Thus, for fair tracking with 10-mil peak excursions and 0.25 SDF, gun aim leads the sight aim by about 15/9 mils for 0.5/1.0 second TOF. For fair tracking and 0.4 SDF, gun aim leads sight aim by about 10/6 mils for 0.5/1.0 second TOF. Because the direction from which the pipper approaches the target is about equi-probable, the statistics of this error source appear to be random/systematic, and should be root-sum-squared with the expected value of the average aim errors. Thus, based on the average period and fair tracking, the gun mean aim errors for a low evasion spectrum (5 mils average pipper error) would be 16/10 mils for 0.5/1.0 second TOF with a 0.25 SDF, excluding all sight and uncertainty errors. For good tracking with pipper peak excursions of 5 mils, the gun mean aim errors for the low evasions spectrum would be 9/7 mils for 0.5/1.0 second TOF with a 0.25 SDF, exclusive of other errors. Acknowledging again the limitations of hopper statistics, a recent fire control study that excluded sensor input errors showed overall rms sighting accuracies of about 12 mils and overall gun aim/miss accuracies in the 17 to 19-mil range. Accounting for mean aim with dynamic errors, other fire control errors including uncertainty would be about 14 mils. Accordingly, while the damped pipper makes the tracking task viable, gun aim errors with the disturbed reticle sight are appreciable, exclusive of sight and uncertainty inaccuracies.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

At present, DATAM-I models the fireline in accordance with the heuristic g and angle-off sensitivity that was previously mentioned, due to the aforementioned calibration with recent combat data and limitations of the Combat Hassle data base. It is recommended that fireline statistics be correlated with encounter difficulty as further analysis of its characteristics indicate.

It is also recommended that the pieces-of-the-problem approach mentioned previously be undertaken to show what their influences are and how they interact.

In conjunction with this approach, it is important to include the user viewpoint. Ensemble statistics are necessary for calibration, but the purpose of the model is to forecast effectiveness of intended application. Accordingly, DATAM-I should be structured to address intended applications, rather than duplication of historical events.

DATAM-I does not presently derive sight or uncertainty errors as a function of encounter geometry. It is proffered that these parameters should be mechanized in a sensitivity study. Those parameters which show significant impact should be incorporated in the mechanics of the model while low sensitivity parameters can be identified in ensemble statistics of the root sum square total of systematic errors.

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